Directivity Loss at a Duct Termination

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ABSTRACT

This paper investigates the directional properties of sound emitted from the end of a long straight duct and has practical applications for the acoustic modelling of exhaust and ventilation systems. It is known that the level of sound at a point remote from the open end of a duct is dependent on frequency, duct area, distance and direction.

As the angle between the duct centreline and a remote point increases the sound level decreases. This loss due to directivity is termed ‘directivity loss’. By understanding directivity loss, the modelling and assessment of noise from such ducts and the design of noise control may be conducted with increased accuracy.

At present the quantitative analysis of directivity loss is not well established. The NSW Environment Protection Authority published directivity loss curves in the “Environmental Noise Control Manual” however this data is based on limited testing.

This study has been undertaken to provide a more detailed assessment of duct borne directivity loss. Testing has been conducted using several different diameters of steel duct and the directivity loss at octave band frequencies has been quantified. Charts relating directivity loss to duct area and frequency have been developed for reference. These directivity loss charts have been compared to the EPA directivity loss chart and the results discussed.

INTRODUCTION

Sound emanating from the end of a long straight duct is directional. This is because the duct transmitting the sound becomes a type of wave-guide, which largely constrains sound to travel within it. Waves can either travel straight down the duct (plane waves) or bounce back and forth between the walls (higher order modes).

The duct can cause transverse waves to be cancelled and therefore create a plane wave. A plane wave is a wave where the sound propagates in a single direction i.e. the lines for uniform phase are straight and the sound pressure level remains constant over the cross section of the duct and with distance along the duct. A wave emitted from a duct termination tends to beam in the direction of the discharge opening.

Plane wave propagation occurs below the cut off/cut on frequency. Above the cut off frequency higher order modes begin. The cut off frequency for round ducts can be estimated using the equation below, as plotted in Figure 1.

$$N = \left(\frac{f_{co}D}{c}\right)^2 + 1.5\left(\frac{f_{co}D}{c}\right)$$

Where: N = integer mode number, f_{co} = cut off frequency (Hz), D = duct diameter (m), c = speed of sound in air (m/s)

Basically plane wave propagation occurs when the wavelength is large compared to the diameter of the duct. The wavelength must be at least twice the cross-sectional diameter of the duct for plane wave propagation to occur inside the duct. Below this wavelength the frequency spectrum is dominated by higher order modes. Figure 1 shows the plane wave region for various diameter ducts.

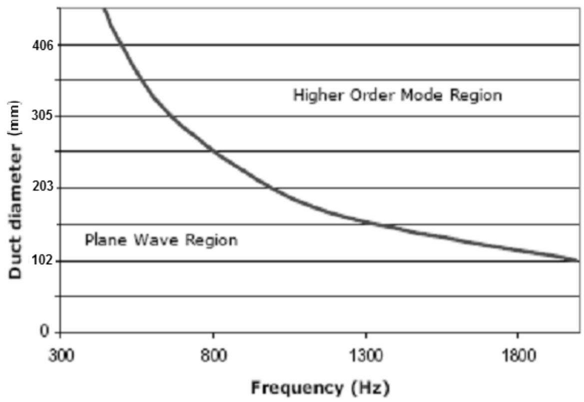


Figure 1: Round Duct Plane Wave vs. Higher Order Mode Regions

Not all sound energy travelling along a duct is emitted from the outlet, an insignificant amount of energy is lost due to absorption of the duct walls and some energy escapes due to the transmission loss though the walls of the duct, called breakout noise. The rigidity and mass of the constraining duct will vary the amount of energy lost due to absorption and breakout. The heavier the mass and stiff the rigidity of the duct the more effective in containing sound energy it will be.

As sound emanating from a duct opening has directional properties it does not dissipate in the same manner as a point source. Rather the sound reduces by varying amounts as a function of frequency, duct area and distance from the outlet. It is known that as the angle between the duct centreline and a remote point increases the sound level decreases. This loss due to directivity is termed ‘directivity loss’.

Examples of situations where directivity loss may need to be considered in a noise assessment include large engine exhaust ducts, air conditioning intake and exhaust ducts, factory chimneys, power station exhaust ducts, steam discharge ducts and kitchen exhaust ducts. The noise emitted from such applications is typically broadband in nature and tonal noise is rarely encountered.

Duct directivity loss testing with ducts of true magnitudes has been carried out previously by Mr Athol Day for Vokes Engineering in 1971 and the results, in the absence of any other test data, are presented as a series of curves in the NSW Environment Protection Authority (EPA) Environmental Noise Control Manual Data Sheet 207-1(1994) Appendix 3 as shown below.

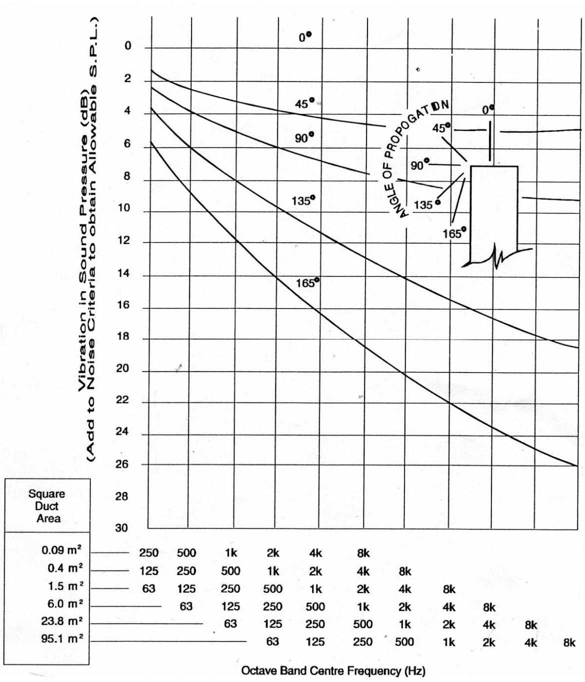


Figure 2: Directivity Loss in a Free Field (EPA Data Sheet 207-1,1994)

These curves are used to determine the directivity loss for single octave band frequencies, with an allowance made for duct area. The Vokes test data was based upon testing of one 660 x 660 mm and one 305 mm x 305 mm square duct. The directivity loss curves were interpolated from the most conservative results.

Mr Murray Neish also conducted directivity loss testing of 400 mm and 1220 mm diameter round ducts, between 1995 to 1997, for his final year university project. The results of his testing determined that the NSW EPA directivity loss curves are conservative, particularly at the higher reference angles and frequencies.

However, like the Vokes test data, current directivity loss curves have been generated from two pipe areas only. More tests of other intermediate duct sizes, nominally 300 mm, 600 mm and 900 mm diameters, are needed to validate the test data for duct sizes that are commonly encountered in noise assessments. Exhaust ducts are usually more than 8 diameters long.

In this paper an attempt to study the effect of lengthening the duct has been conducted to investigate any changes in directivity loss. The effect of the measurement distance from the duct termination was also investigated to determine whether or not this has an effect on directivity loss possibly due to noise lobes.

This aim of this study is to further determine the extent of directivity loss expected at various sized duct terminations and validate or prove otherwise the currently used directivity loss data.

The results of this study may be used as a more comprehensive directivity loss reference for use by acousticians to further understand directivity loss and improve the accuracy of modelling noise emission for use in noise assessments, taking into account directivity loss, from the termination of a long straight duct as found in many industrial applications.

METHODOLOGY

To accurately quantify the amount of directivity loss expected from ducts that are commonly encountered in industry testing needs to be carried out on ducts of true magnitude. This poses a practical problem as such ducts are not readily accessible and typically exhaust vertically, with their discharge at a height that is impractical for a directivity loss assessment. Furthermore it is expected that a large number of other noise sources, such as other noisy plant, traffic, etc would be found in the near vicinity of industrial discharge ducts, which cannot be turned off, and would interfere with directivity loss testing.

The only feasible and practical way to carry out such testing was deemed to use an artificial noise source, in a duct with a diameter common in industry, with sufficient length, set up horizontally and elevated to an accessible height, in a location where the level of background noise would not affect measurements. The test rig setup is detailed below.

Pipe Selection

It is useful to be able to quantify the amount of directivity loss expected at all duct diameters however testing of every duct size is not practical and therefore three of the most common sizes found in industrial applications, being 305 mm, 610 mm and 914 mm were selected to be used for the directivity loss measurements.

Ideally the use of a thick/heavy walled pipe (high STC) of a material such as terracotta or concrete would be used for testing, however due to the large diameters and lengths required such materials would be far too heavy to handle. Following the evaluation of several ducting types, spiral wound circular steel piping was selected for the testing, due to its benefit of being cost effective and relatively light weight with high transmission loss properties.

It was decided that testing would be conducted on varying lengths of ducts to determine whether or not the change in length influences directivity loss.

Noise Source

Pink noise was generated and amplified through an E-Tone SUP 12SA (250 W) loudspeaker with inbuilt amplifier. This speaker is capable of achieving sufficient levels of sound (above 85 dB) in all frequencies. With a maximum directivity loss of 30 dB expected the source noise level at our measurement locations would still be at least 10 dB above background noise levels and hence background noise would not influence results.

Test Setup

To conduct such tests a free field environment is required as access to a very large anechoic lab is near impossible. The test rig was constructed on a rural property in Bargo, NSW as this location had ample space, no time constraints and a low level of background noise, 34 – 39 dBA during the day.

The duct to be tested was orientated horizontally and the centreline of the duct was raised 2.7 m above the ground for the 305 mm and 610 mm diameters and 1.4 m above the ground for the 914 mm diameter. The centreline of the 914 mm duct was only raised to a height of 1.4 m as it was not able to be lifted to a greater height, due to its weight.

The 305 mm and 610 mm diameter ducts were supported on one end by a water tank and on the other end by a steel structure as shown in Figure 3 below. The 914 mm duct was supported on scaffolds and the tray of a tractor as shown in Figure 4 below.

The ducts and speaker enclosure were lagged with polyester insulation (MSB 4, 75 mm, 8.7 kg/m^3) and 8 kg/m^2 'Wavebar' loaded vinyl to minimise breakout noise.


Figure 3: Testing apparatus of 305 mm duct at Bargo


Figure 4: Testing apparatus of 914 mm duct at Bargo

To couple the 305 mm and 610 mm round ducts to the rectangular speaker a 18 mm thick particleboard box (0.4 m x 0.7 m x 0.7 m) was constructed. The speaker was enclosed inside and a round hole was cut to size in the front face of the box for the duct to be inserted. To eliminate flanking transmission, small gaps inside the speaker enclosure were sealed with sound rated mastic and insulation and loaded vinyl were draped over the speaker enclosure.

For the directivity loss testing of the 914 mm duct the speaker was placed inside the end of the duct and that end of the duct sealed closed with a 18 mm particleboard end stop.

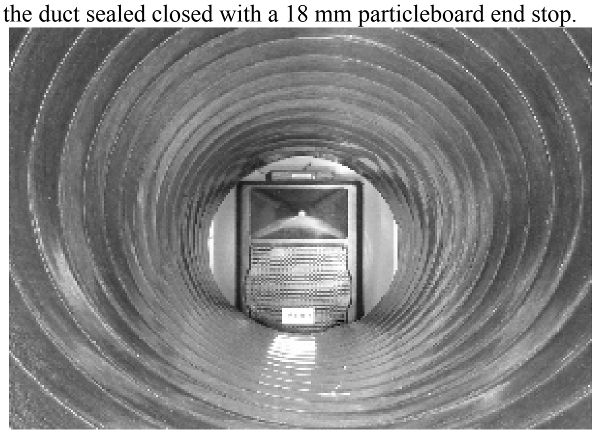


Figure 5: View of speaker inside duct

To determine the effect of lengthening the duct, standard duct lengths were joined together. This was achieved with the 610 mm and 914 mm diameter ducts, where lengths of the ducts where joined together with duct coupling joiners to increase the overall length.

Measurement Procedure

Once the test rig was set up pink noise was generated in the duct. Sound pressure level measurements were conducted using a B & K 2260 precision sound level analyser with a 1/3 octave band filter at 15˚ intervals ranging from 0˚ to 165˚ as shown in Figure 6. The $L_{eq,30}$ sec noise level was measured at each interval. The measured sound pressure level data was processed to obtain directivity loss at varying angles and frequencies. Directivity loss was calculated by subtracting the sound pressure level at each reference angle from the sound pressure level at the 0° reference angle.

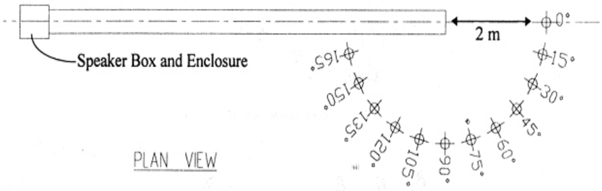


Figure 6: Measurement Schematic

Directivity loss measurements were conducted on the 7 and 8 July 2006. Various test geometries and distances from the duct termination, as shown in Figure 7, were measured to quantify directivity loss with an attempt made to understand how the duct diameter, length and distance from termination affects directivity loss.

All measurements were conducted in the far field that begins at 3.3 x diameter of the duct as well as at further distances to determine the effects of possible noise lobes.

The directivity loss of the following test configurations was measured:

Duct Diameter	Duct Length	Radius of Measurement
305 mm	3 m	1 m & 3 m
610 mm	3 m	2 m
610 mm	6 m	2 m & 4 m
914 mm	4.8 m	3 m
914 mm	7.8 m	3 m & 6 m

Figure 7: Test Configurations

Additional measurements were conducted at large distances (9 m and 20 m) at reference angles of 0, 45 and 90 degrees to validate close proximity measurements and to investigate whether there were any noticeable changes in directivity loss with large distances. Measurements were also conducted along the length of the duct at a distance of 300 mm from the duct surface to be used for analysis of breakout noise if required.

RESULTS

Following conduction of directivity loss tests on various pipe diameters and lengths, collation of the data and processing of results the generation of directivity loss curves in graphical form is as shown in Figures 8 to 15 below.

Directivity Loss at a Duct Termination

Notation: Duct Diameter, Duct Length @ Measurement Distance from Duct Termination (Example: Ø 305/3000 mm @ 1 m).

Legend:

63 Hz, 125 Hz, 250 Hz, 500 Hz

1 kHz, 2 kHz, 4 kHz, 8 kHz

The directivity loss as graphed in Figures 8 & 9, was determined for a Ø 305 mm, 3 m long duct, measured at both 1 m and 3 m from the duct termination.

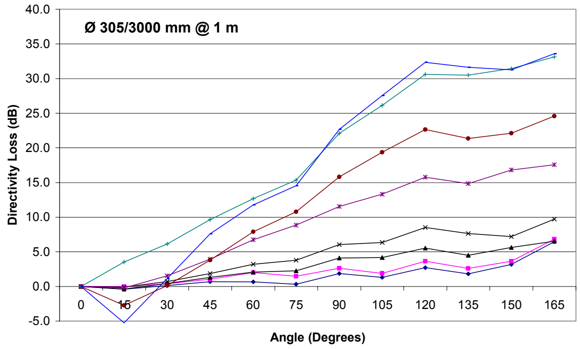


Figure 8: Ø 305/3000 mm @ 1 m

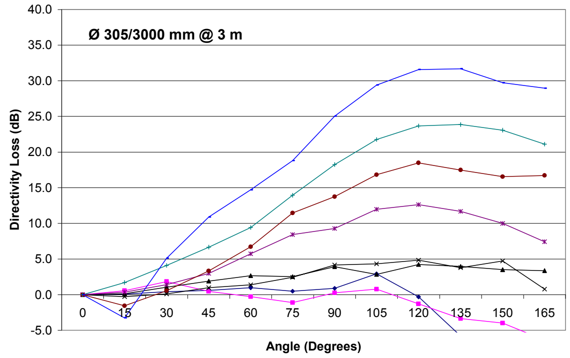


Figure 9: Ø 305/3000 mm @ 3 m

The directivity loss as graphed in Figure 10, was determined for a Ø 610 mm, 3 m long duct, measured at 2 m from the duct termination.

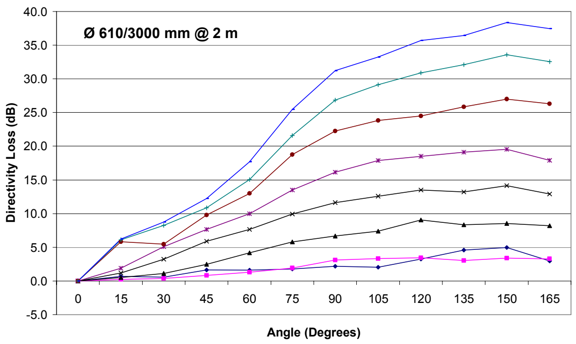


Figure 10: Ø 610/3000 mm @ 2 m

Figures 11 & 12 show the directivity loss of an extended duct of 6 m in length, measured at 2 m and 4 m from the duct termination.

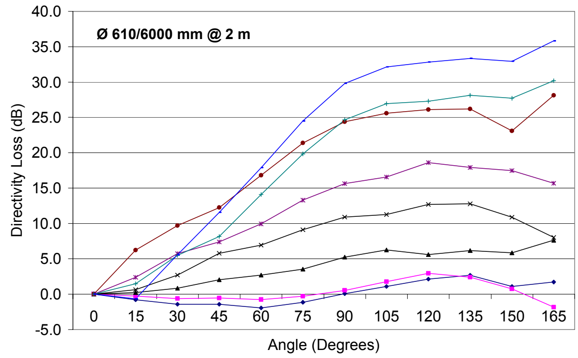


Figure 11: Ø 610/6000 mm @ 2 m

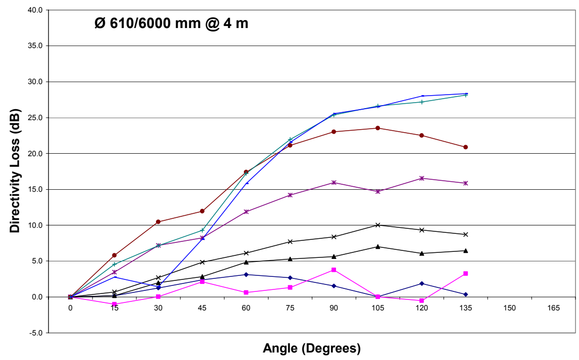


Figure 12: Ø 610/6000 mm @ 4 m

The directivity loss as graphed in Figure 13, was determined for a Ø 914 mm, 4.8 m long duct, measured at 3 m from the duct termination.

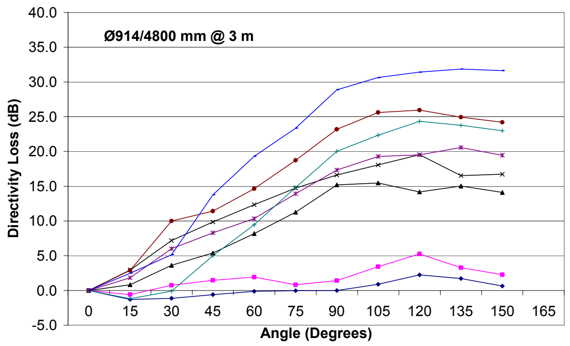


Figure 13: Ø 914/4800 mm @ 3 m

Figures 14 & 15 show the directivity loss of an extended duct of 7.8 m in length, measured at 3 m and 6 m from the duct termination.

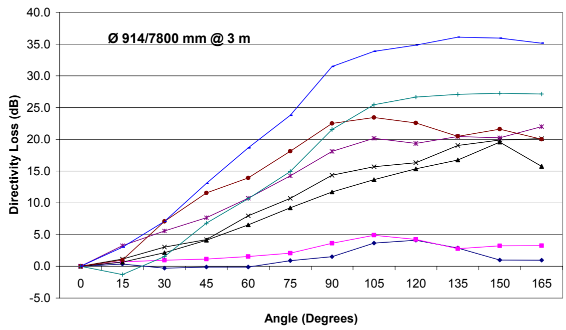


Figure 14: Ø 914/7800 mm @ 3 m

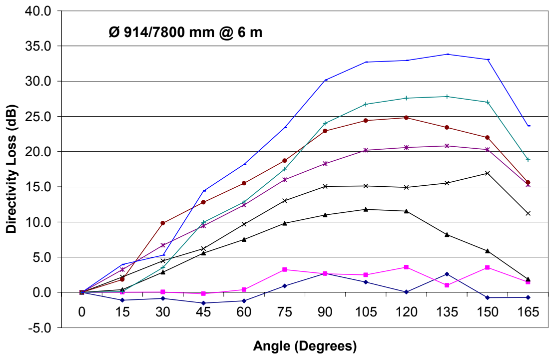


Figure 15: Ø 914/7800 mm @ 6 m

The ambient background noise level during the measurements ranged between 34 and 39 dBA. The generated source noise level was typically 90 dBA at the 0 degree reference angle and 55 dBA at the 165 degree reference angle, therefore more than 10 dBA in excess of the ambient noise level so results were not influenced by the background noise level. No corrections for background noise were required. However corrections for breakout noise at large reference angles and distances were required.

DISCUSSION

Directivity Loss Results

From the directivity loss curves it can be seen that the higher frequencies are more directive than the lower frequencies. It is almost uncanny that the directivity loss graphs are so ordered showing the directivity loss to reduce from 8 kHz to 63 Hz in almost perfect order with minimal overlap of the frequencies.

High frequencies are more directive in nature due to their shorter wavelengths. It was originally expected that the low frequencies would exhibit more directive loss than high frequencies as they are travelling as plane waves in the duct, whereas the high frequencies are travelling as higher order modes. Although the low frequencies are travelling as a plane wave in the duct, upon exiting the duct they soon dissipate into a spherical wave at approximately 3.3 x diameter of the duct. All measurements were conducted in the far field region and hence plane wave propagation in the duct is not the only factor influencing directivity loss.

In general the 63 Hz and 125 Hz frequencies did not exceed a 5 dB directivity loss at any reference angle. However, it was found that the larger the diameter of the duct the more directivity loss is exhibited at the low and mid frequencies. If larger diameter ducts were used an increase in directivity loss at the low frequencies would be expected.

An example of this is shown if 90 degrees and 1 kHz is taken as the subject angle and frequency. The Ø 305/3000 @ 3 m achieves 8 dB, Ø 610/6000 @ 2 m achieves 16 dB and the Ø 914/7800 @ 3 m achieves 18 dB directivity loss.

The diameter of the duct did not significantly influence the directivity loss at high frequencies.

At 15° in the Ø 305/3000 mm tests the 2 kHz and 8 kHz frequencies actually exhibited a directivity gain not loss. This could possibly be due to noise lobes or the directive nature of these frequencies where they could possibly be reflected out of the duct at 15°. This gain is considered to be an anomaly rather than a normality.

The Ø 610/6000 mm @ 4 m was only measured to a reference angle of 135° due to the supporting structure preventing measurements at larger reference angles and the Ø 914/4800 mm @ 3 m to a reference angle of 150° due to the large diameter of the duct causing 165° to be against the duct wall.

Breakout out noise was controlled by wrapping the ducts with insulation and loaded vinyl and in most cases did not influence directivity loss measurements. However in cases where the measurement distance from the duct termination was large or at large reference angles i.e. above 120 degrees the directivity loss reduced. This is contrary to the expected increase in directivity loss at larger reference angles and is caused by the breakout noise contribution either through the duct or speaker enclosure, which in turn reduces the calculated directivity loss.

Cases where breakout noise affected results was at large reference angles as shown in Figures 9, 12, 13 and 15. In all these cases at angles above 120 degrees the directivity loss either became linear or dropped in magnitude rather than increasing as would be expected. Most of the breakout in the 305 mm and 610 mm testing occurred through the speaker box enclosure rather than through the duct but generally was not noticeable at reference angles less than 120°. Breakout noise occurred through the joins and the plugged end of 914 mm diameter duct.

The lengthening (doubling in length) of the duct caused no noticeable changes in directivity loss. The only improved directivity loss was noticed in the Ø 610/3000 mm @ 2 m and Ø 610/6000 mm @ 2 m at the 2 kHz frequency.

Measurements at different distances were conducted to determine the effect of noise lobes. No noise lobes were noticed except for at 75° in the Ø 305/3000 mm @ 1 m and @ 3 m distances where variations in directivity loss were noticed and possibly due to noise lobes.

Measurements at large distances (9 m and 20 m) from the duct termination were conducted and generally correlated with results from the close proximity measurements however there were occasional discrepancies noticed at different frequencies by either an increase or decrease in directivity loss. These discrepancies are generally within 5 dB. Break out noise was considered an influencing factor at these larger distances and accounts for the slightly contaminated directivity loss measurements at the 90° reference angle.

At the 0° reference angle it was noticed that as the distance from the duct termination was increased the sound pressure level decreased but not as a point source (6 dB per doubling of distance). This is expected as the sound is being emitted with directional properties. At 45° and 90° the sound pressure generally decreased as would a point source. Therefore to calculate the sound pressure at a location far from the end of a duct termination the sound power of the discharge may be used, corrected for directivity loss and then distance attenuation applied.

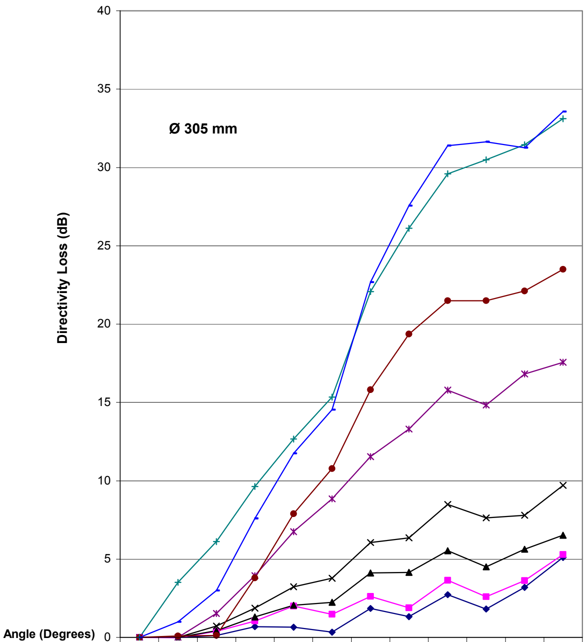
Results show that as a general rule of thumb for a broadband noise emitted from a long straight duct you could expect an overall dBA directivity loss of 7 dBA at 45°, 17 dBA at 90° and 20 dBA at 135°. This is a general conservative rule of thumb and for increased accuracy directivity loss at individual frequencies should be considered.

The directivity loss curves from raw data may be used to predict the directivity loss at various duct diameters and frequencies. Due to the contribution of breakout noise, which reduces the directivity loss at high reference angles the directivity loss above 120° would be deemed conservative.

The effect of breakout noise has been considered and removed to provide graphs, as shown below, in Figures 16, 17 and 18 to be used as a reference for directivity loss in the modelling and assessment of industrial noise emission from the termination of a long straight round duct.

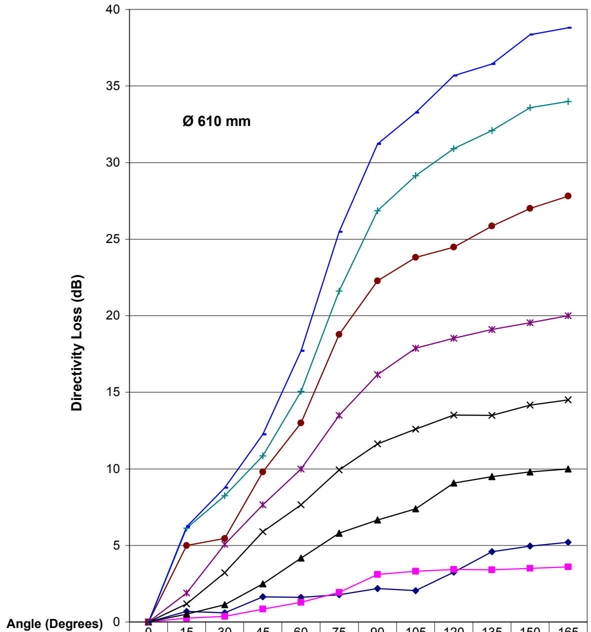
Interpolation, trendlines and acoustical opinions have been used to negate the effect of breakout from the measured directivity loss curves and the results are shown below.

The following graphs are intended to provide a guide to the directivity loss expected from an open ended long straight duct. The effect of other factors including larger duct areas, reflective surfaces, hoods that may disperse noise, breakout noise, etc should also be considered.



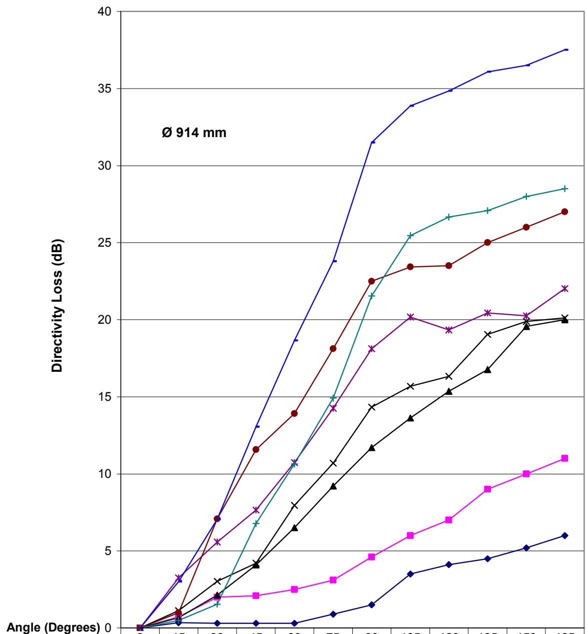
Angle (Degrees)	0	15	30	45	60	75	90	105	120	135	150	165
63 Hz	0	0	0	1	1	0	2	1	3	2	3	5
125 Hz	0	0	0	1	2	1	3	2	4	3	4	5
250 Hz	0	0	0	1	2	2	4	4	6	5	6	7
500 Hz	0	0	1	2	3	4	6	6	9	8	8	10
1 kHz	0	0	2	4	7	9	12	13	16	15	17	18
2 kHz	0	0	0	4	8	11	16	19	22	22	22	24
4 kHz	0	4	6	10	13	15	22	26	30	30	31	33
8 kHz	0	1	3	8	12	15	23	28	31	32	31	34

Figure 16: Ø 305 mm Duct Directivity Loss



Angle (Degrees)	0	15	30	45	60	75	90	105	120	135	150	165
63 Hz	0	1	1	2	2	2	2	2	3	5	5	5
125 Hz	0	0	0	1	1	2	3	3	3	3	4	4
250 Hz	0	1	1	2	4	6	7	7	9	10	10	10
500 Hz	0	1	3	6	8	10	12	13	14	14	14	15
1 kHz	0	2	5	8	10	14	16	18	19	19	20	20
2 kHz	0	5	5	10	13	19	22	24	24	26	27	28
4 kHz	0	6	8	11	15	22	27	29	31	32	34	34
8 kHz	0	6	9	12	18	25	31	33	36	36	38	39

Figure 17: Ø 610 mm Duct Directivity Loss



Angle (Degrees)	0	15	30	45	60	75	90	105	120	135	150	165
63 Hz	0	0	0	0	0	1	2	4	4	5	5	6
125 Hz	0	1	2	2	3	3	5	6	7	9	10	11
250 Hz	0	1	2	4	7	9	12	14	15	17	20	20
500 Hz	0	1	3	4	8	11	14	16	16	19	20	20
1 kHz	0	3	6	8	11	14	18	20	19	20	20	22
2 kHz	0	1	7	12	14	18	22	23	24	25	26	27
4 kHz	0	1	2	7	11	15	22	25	27	27	28	29
8 kHz	0	3	7	13	19	24	31	34	35	36	37	38

Figure 18: Ø 914 mm Duct Directivity Loss

Evaluation Against EPA Directivity Loss Chart and Mr Murray Neish's Thesis

The new directivity loss results were compared to the NSW EPA directivity loss curves in Appendix 3 of the Environmental Noise Control Manual (1994) and Mr Neish's directivity loss testing.

The results of the testing have determined that the current NSW EPA directivity loss curves are very conservative, particularly at the higher reference angles and frequencies.

The results of these tests correlate well with the directivity loss measurements by Mr Murray Neish in 1995-1997.

CONCLUSION

Free-field duct directivity loss was determined for 305 mm, 610 mm and 914 mm duct diameters. Directivity loss was found to increase with larger reference angles and higher frequencies and increase at the low and mid frequencies by increasing the duct area.

Comparison of the test results against the EPA directivity loss curves shows that the EPA results are conservative, under predicting directivity loss at the higher reference angles and frequencies.

The results of this study may be used as a more comprehensive directivity loss reference.

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